TSDT14 Signal Theory

Lecture 9

Reconstruction and Reconstruction Errors

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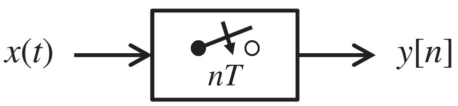
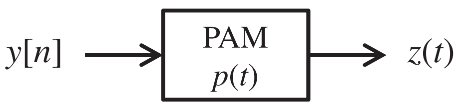
Sampling and PAM of Deterministic Signals – Summary



$$y[n] = x(nT)$$

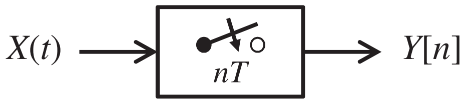
$$Y[\theta] = \frac{1}{T}\sum_m X\left(\frac{\theta - m}{T}\right)$$



$$z(t) = \sum_n y[n]\, p(t - kT)$$

$$Z(f) = P(f)Y[fT]$$

Sampling and PAM of WSS Processes – Summary

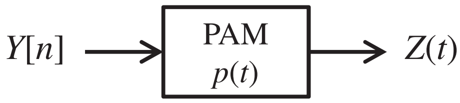


$$Y[n] = X(nT)$$

$$m_Y = m_X$$

$$r_Y[k] = r_X(kT)$$

$$R_Y[\theta] = \frac{1}{T}\sum_m R_X\left(\frac{\theta - m}{T}\right)$$



$$Z(t) = \sum_n Y[n]\, p(t - kT - \Psi)$$

Ψ unif. $[0, T]$
Ψ & $Y[n]$ indep.

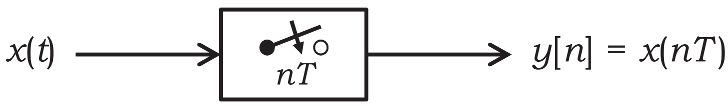
$$m_Z = \frac{1}{T} P(0) m_Y$$

$$r_Z(\tau) = \frac{1}{T}\sum_k r_Y[k](p * \tilde{p})(\tau - kT)$$

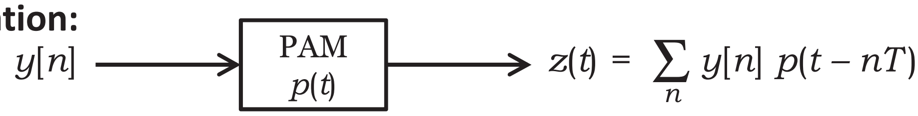
$$R_Z(f) = \frac{1}{T}|P(f)|^2 R_Y[fT]$$

Linear Mappings

Sampling:

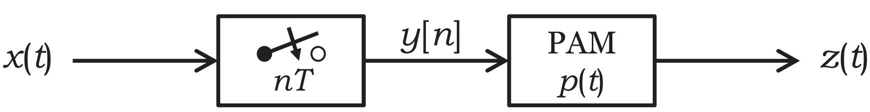


Pulse-Amplitude Modulation: (PAM)

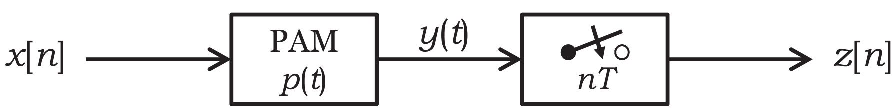


Reconstruction:

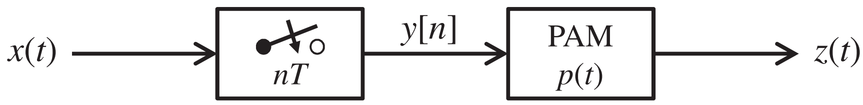
$t \to n \to t:$



$n \to t \to n:$



Sampling Theorem for Deterministic Signals



The Sampling Theorem:

Consider a signal $x(t)$, with spectrum $X(f)$ and $X(f) = 0$ for $|f| \geq f_0$. If $x(t)$ is sampled with sampling frequency f_s, then $x(t)$ can be reconstructed without error from the sampled signal if $f_s \geq 2f_0$ holds.

This means:

There exists a pulse shape $p(t)$, such that $x(t)$ can be written as

$$x(t) = \sum_n x(nT)\, p(t - nT)$$

if $f_s \geq 2f_0$ holds, where $f_s = 1/T$.

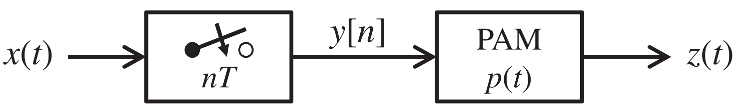
Fulfilled for:

Ideal reconstruction: $p(t) = \mathrm{sinc}(t/T)$

Reconstruction – Deterministic Case

$t \rightarrow n \rightarrow t$:

$$y[n] = x(nT) \qquad Y[\theta] = f_s \sum_m X((\theta - m) f_s)$$



$$z(t) = \sum_n y[n] p(t - nT) \qquad Z(f) = P(f) Y[f / f_s]$$

Total spectrum:

$$Z(f) = $$
$$= f_s P(f) \sum_m X(f - m f_s)$$

Distorsion:

$$\varepsilon^2 = \int_{-\infty}^{\infty} (z(t) - x(t))^2\, dt \overset{\text{Parseval}}{=} \int_{-\infty}^{\infty} |Z(f) - X(f)|^2\, df$$

$$= \int_{-\infty}^{\infty} \left| f_s P(f) \sum_m X(f - m f_s) - X(f) \right|^2 df = \int_{-\infty}^{\infty} \left| (f_s P(f) - 1) X(f) + f_s P(f) \sum_{m \neq 0} X(f - m f_s) \right|^2 df$$

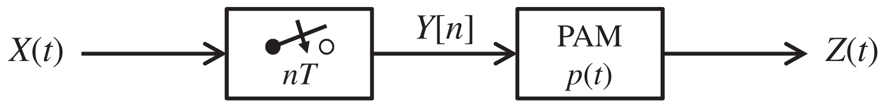
Ideal reconstruction:

$p(t) = \mathrm{sinc}(t/T)$

$P(f) = T\,\mathrm{rect}(fT)$

$$\varepsilon^2 = \underbrace{2 \int_{f_s/2}^{\infty} |X(f)|^2\, df}_{\text{Bandlimiting distorsion}} + \underbrace{2 \int_0^{f_s/2} \left| \sum_{m \neq 0} X(f - m f_s) \right|^2 df}_{\text{Aliasing distorsion}}$$

The Sampling Theorem for Stochastic Processes



The Sampling Theorem:

Consider a process $X(t)$, with spectrum $R_X(f)$ and $R_X(f) = 0$ for $|f| \geq f_0$. If $X(t)$ is sampled with sampling frequency f_s, then $X(t)$ can be reconstructed without error from the sampled signal if $f_s \geq 2f_0$ holds.

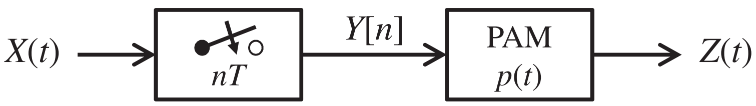
This means:

There exists a pulse shape $p(t)$, such that $\varepsilon^2 = \mathrm{E}\left\{ (Z(t) - X(t))^2 \right\} = 0$ holds.

Fulfilled for:

Ideal reconstruction: $p(t) = \mathrm{sinc}(t/T)$

Proof of Sampling Theorem 1(2)



$$Z(t) = \sum_n X(nT)p(t-nT)$$

No need for Ψ.

Distorsion: $\varepsilon^2 = \mathrm{E}\left\{(Z(t) - X(t))^2\right\} = \mathrm{E}\left\{Z^2(t)\right\} - 2\mathrm{E}\left\{Z(t)X(t)\right\} + \mathrm{E}\left\{X^2(t)\right\}$

$$\mathrm{E}\left\{Z^2(t)\right\} = \mathrm{E}\left\{\left(\sum_n X(nT)p(t-nT)\right)^2\right\} = \sum_m \sum_n \mathrm{E}\left\{X(nT)X(mT)\right\}p(t-nT)p(t-mT)$$

$$= \sum_m \left(\sum_n r_X(nT - mT)p(t-nT)\right)p(t-mT)$$

$$\mathrm{E}\left\{Z(t)X(t)\right\} = \mathrm{E}\left\{\sum_n X(nT)p(t-nT)X(t)\right\} = \sum_n \mathrm{E}\left\{X(nT)X(t)\right\}p(t-nT)$$

$$= \sum_n r_X(nT - t)p(t-nT)$$

$$\mathrm{E}\left\{X^2(t)\right\} = r_X(0)$$

Proof of Sampling Theorem 2(2)

We had:

$$\mathrm{E}\{Z^2(t)\} = \sum_m \left(\sum_n r_X(nT - mT)p(t - nT) \right) p(t - mT)$$

$$\mathrm{E}\{Z(t)X(t)\} = \sum_n r_X(nT - t)p(t - nT)$$

Try ideal reconstruction:

$$p(t) = \mathrm{sinc}(t/T)$$

From the deterministic case: $r_X(\tau) = \sum_m r_X(mT)p(\tau - mT)$

$$r_X(\tau - a) = \sum_n r_X(nT)p(\tau - a - nT) = \sum_n r_X(nT - a)p(\tau - nT) \quad \mathbf{(1)}$$

With $\tau = t$ & $a = mT$ in (1), we get : $r_X(t - mT) = \sum_n r_X(nT - mT)p(t - nT)$ **(2)**

With $\tau = a = t$ in (1), we get : $r_X(0) = \sum_n r_X(nT - t)p(t - nT)$ **(3)**

$$\mathbf{(2)}\ \&\ \mathbf{(3)} \Rightarrow \quad \mathrm{E}\{Z^2(t)\} = \sum_m r_X(t - mT)p(t - mT) = \sum_m r_X(mT - t)p(t - mT) = r_X(0)$$

$$\mathbf{(3)} \Rightarrow \quad \mathrm{E}\{Z(t)X(t)\} = r_X(0)$$

Result: $\varepsilon^2 = 0$

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